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DESIGN CONFIGURATIONS FOR VERY HIGH TEMPERATURE GAS-COOLED REACTOR DESIGNED TO GENERATE ELECTRICITY AND HYDROGEN

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ABSTRACT

The High Temperature Gas-Cooled Reactor is being envisioned that will generate not just electricity, but also hydrogen to charge up fuel cells for cars, trucks and other mobile energy uses. INL engineers studied various heat-transfer working fluids—including helium and liquid salts—in seven different configurations. In computer simulations, serial configurations diverted some energy from the heated fluid flowing to the electric plant and hydrogen production plant.

In anticipation of the design, development and procurement of an advanced power conversion system for HTGR, this study was initiated to identify the major design and technology options and their tradeoffs in the evaluation of power conversion system (PCS) coupled to hydrogen plant. In this study, we investigated a number of design configurations and performed thermal hydraulic analyses using various working fluids and various conditions (Oh, 2005). This paper includes a portion of thermal hydraulic results based on a direct cycle and a parallel intermediate heat exchanger (IHX) configuration option.

KEY REQUIREMENTS AND ASSUMPTIONS

Two top-level temperature requirements have been identified for the interface between the nuclear and hydrogen plants. These requirements are defined by the outlet temperature of the high-temperature reactor and the maximum temperature delivered to the hydrogen plant. At this stage of development, these maximum system temperatures are active areas of investigation, and parametric studies are more appropriate than point design studies. However, for this initial analysis, the outlet temperature of the high-temperature reactor was set at 900 °C, consistent with current capabilities, and parametric calculations were performed with higher outlet temperatures to determine their effects on component performance.

The efficiency of the hydrogen-production process increases with temperature but is also uncertain at this point. The sulfur-based cycles, which are currently the baseline thermochemical cycles, are considered to require at least 850 °C. High-temperature electrolysis current requires temperatures in the range of 750 to 900 °C. For this analysis, the maximum temperature supplied to the hydrogen plant was assumed to be 850 °C.

In order to provide estimates of component performance, assumptions are required about the basic configuration and operating conditions of the high-temperature reactor, the intermediate heat transport loop, and the hydrogen production plant. For this report, the preliminary designs for the Next Generation Nuclear Plant (NGNP) were used as the basis for analysis. The primary assumptions are described below and summarized in Table 1. Parametric calculations were performed to determine the effects of changes from the basic parameters.

The NGNP was assumed to produce 600 MW of thermal power and use helium coolant. The nominal rise in fluid temperature across the core was assumed to be 400 °C, based on the point design (MacDonald et al. 2003). The nominal reactor pressure was assumed to be 7 MPa (INEEL 2005). The pressure drop across the hot stream of the intermediate heat exchanger (IHX) was assumed to be 0.05 MPa. This value is the same as the pressure drop across the core in the Gas Turbine-Modular Helium Reactor (GT-MHR) (General Atomics 1996). Since the pumping power associated with this pressure drop across the core was considered acceptable in the GT-MHR, the pumping power associated with this pressure drop across the IHX should also be acceptable. The same pressure drop was generally applied to other components because of pumping power considerations.

The intermediate heat transport loop was assumed to receive 50 MW of thermal power (ANLW 2004). Parametric calculations were performed in which the total output of the reactor (600 MW) was assumed to be used for hydrogen production.

Estimates for the required separation distance between the nuclear and hydrogen plants depend on the design and safety criteria applied and vary considerably. For example, Verfondern and Nishihara (2004) calculated 300 m for the High-Temperature Engineering Test Reactor in Japan whereas Sochet et al. (2004) recommended 500 m for the High-Temperature Reactor. Smith et al. (2005) recommended a separation distance of from 60 to 120 m for the NGNP and the hydrogen production plant. For this analysis, a nominal value of 90 m was used, with parametric variations between 60 and 500 m. The separation distance primarily affects the diameters and insulation requirements of the hot and cold legs in the heat transport loop.

The nominal temperature drop between the outlet of the NGNP and the maximum temperature delivered to the hydrogen production plant is 50 °C. This temperature drop imposes requirements on the effectiveness of the heat exchangers that connect the NGNP and production plant and the amount of heat loss than can be tolerated in the intermediate loop. In order to perform preliminary calculations, heat loss was assumed to cause the fluid temperature to drop 10 °C in the hot leg of the intermediate loop at nominal conditions. Assuming the same geometry in the hot and cold legs of the intermediate loop, more heat is lost from the hot leg than from the cold leg. Based on nominal temperatures, the heat loss from the hot legs is expected to be about 70% of the total. The total temperature drop in the loop piping was assumed to be 10/0.7 = 14.3 °C, with 10 °C occurring in the hot leg and the remaining 4.3 °C occurring in the cold leg. Using a nominal flow rate, the resulting heat losses in the hot and cold legs were 1.25 and 0.54 MW, respectively. This heat loss corresponds to 3.6% of the loop power and 0.3% of the nuclear reactor power. The same heat loss was assumed for all configurations to allow consistent comparisons.

Table 1. Analysis assumptions.

Parameter	Nominal Value
NGNP:	
Power, MW	600
Outlet temperature, °C	900
Core temperature rise, °C	400
Pressure, MPa	7
IHX pressure drop, MPa	0.05
Intermediate heat transport loop:	
Power, MW	50
Separation distance, m	90
Heat loss, MW	1.79
Hydrogen plant:	
Maximum delivered temperature, °C	850
Inlet fluid temperature, °C	341

The IHX is assumed to be a compact heat exchanger of the type designed by Heatric (Dewson and Thonon 2003). The heat exchanger that connects the heat transport loop to the hydrogen production plant is referred to as the process heat exchanger (PHX) and is assumed to be a tube-in-shell heat exchanger with the heat transport fluid flowing on the shell side. This configuration allows the tubes to contain the catalysts necessary for hydrogen production, which is judged to be the most convenient configuration. The tube side was assumed to be at low pressure (< 1 MPa). The hot and cold legs of the intermediate loop are assumed to be separate pipes, as opposed to an annular configuration. The purpose of these calculations is to compare the relative size of components between configurations. These calculations are not intended to achieve a final design for any configuration or to recommend one type of heat exchanger over another.

The required size of the heat exchangers depends on the overall temperature difference between the outlet of the reactor core and the inlet on the cold side of the PHX. For this analysis, the inlet temperature on the cold side of the PHX was assumed to be 341 °C to allow consistent comparisons between the various configurations. This value is reasonable for both thermochemical and high-temperature electrolysis production methods.

DESIGN CONFIGURATIONS

Seven plant configurations were evaluated as part of this task. For convenience, the following nomenclature is used relative to the heat exchangers:

- IHX - The first heat exchanger downstream of the NGNP outlet
- PHX - The heat exchanger that connects the intermediate heat transport loop to the hydrogen production plant
- SHX - The heat exchanger that, if present, is located between the IHX and the PHX, and is referred to as the secondary heat exchanger (SHX).

The seven plant configurations evaluated are illustrated in Figures 1 through 7. The configurations include direct and indirect electrical cycles as shown in Figures 1 – 4 and 5 – 7, respectively. The configurations include both serial and parallel heat exchanger options. In the serial option, which is illustrated in Figures 1, 3, and 5, the IHX or SHX is located upstream of the power conversion unit (PCU). In the serial option, the heat exchanger removes less than 10% of the reactor power and directs it towards the hydrogen production plant. With this configuration, the hydrogen production plant receives the highest possible temperature fluid while the PCU receives a lower temperature fluid. This configuration is relatively simple and is especially suitable for the demonstration of hydrogen production. However, the overall efficiency of the electrical production process will be reduced. In the parallel heat exchanger option, which is illustrated in Figures 2, 4, 6, and 7, the hottest fluid is divided, with most going towards the PCU and the remainder going towards the hydrogen production plant. This configuration is more complicated, but results in a higher overall efficiency because both the electrical and hydrogen production plants see the maximum possible temperature. With these options, a small compressor or blower is required to compensate for the pressure loss across the IHX or SHX and allow the fluid streams to mix downstream of the recuperator. The final option uses a SHX as shown in Figures 3, 4, 5, and 6. This option utilizes a third or tertiary coolant loop that provides additional separation between the nuclear and hydrogen plants, which should increase the safety of both plants and may make the nuclear plant easier to license. However, this option requires more capital investment and lowers the overall efficiency of the plant.

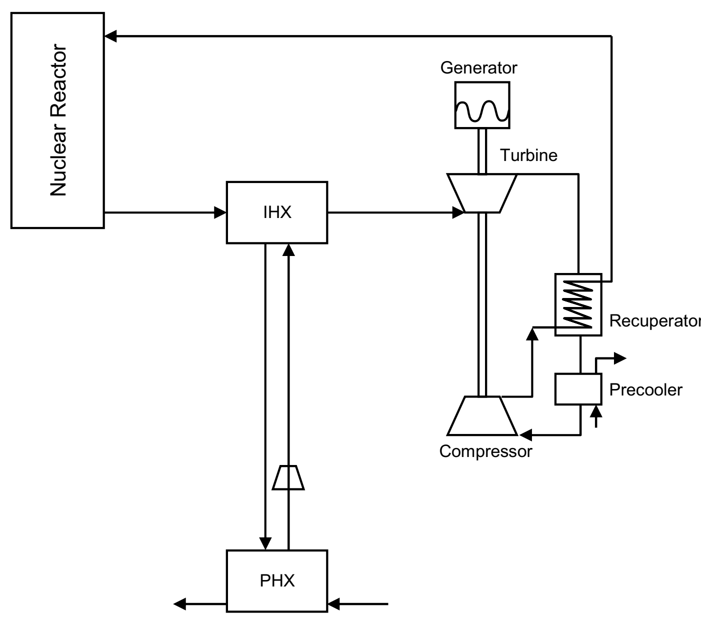

Figure 1. Configuration 1 (direct electrical cycle and a serial IHX).

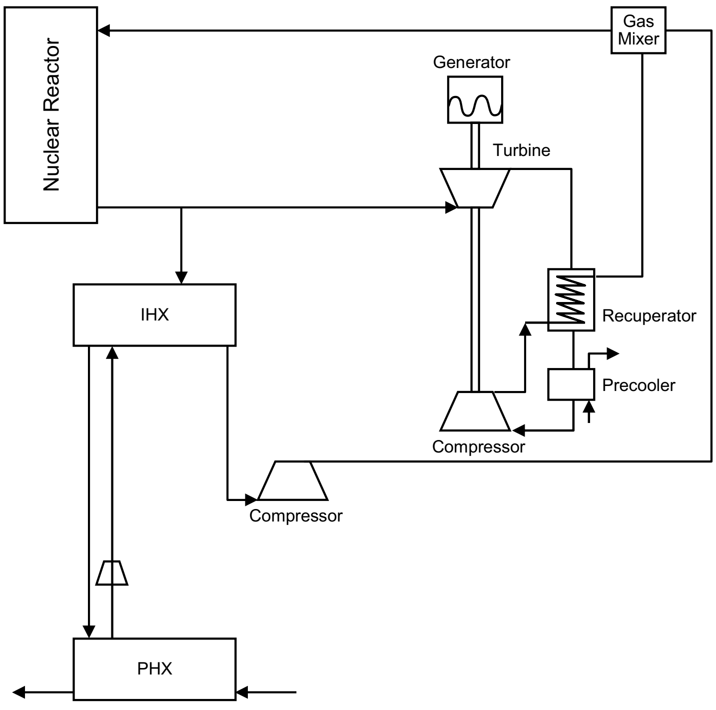

Figure 2. Configuration 2 (direct electrical cycle and a parallel IHX).

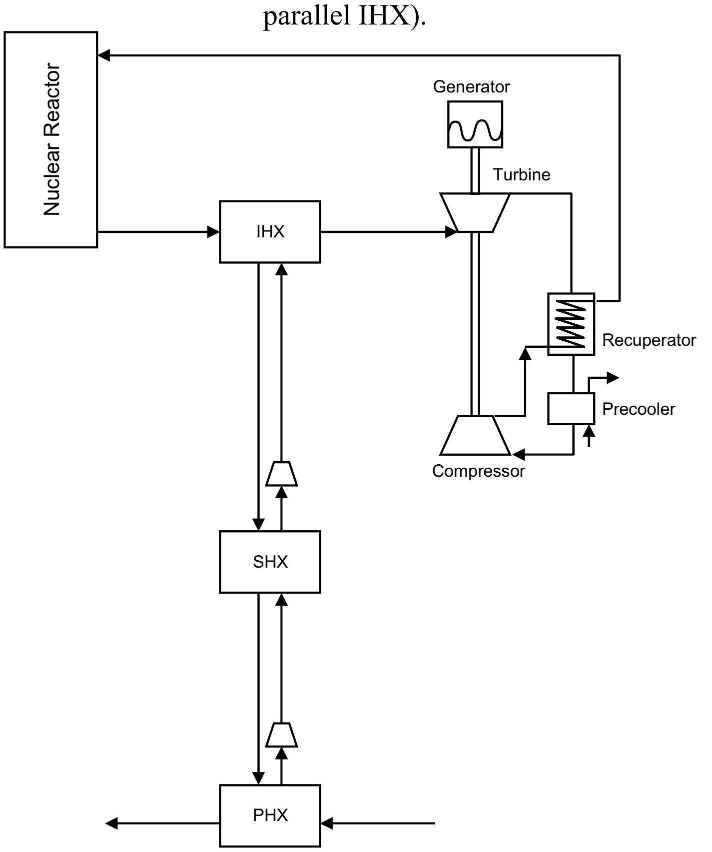

Figure 3. Configuration 3 (direct electrical cycle, serial IHX, and SHX).

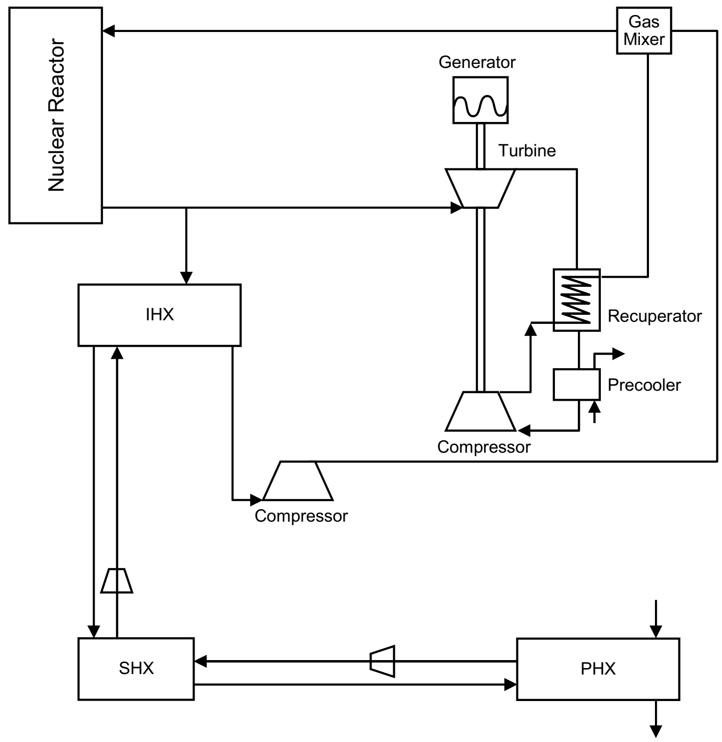

Figure 4. Configuration 4 (direct electrical cycle, parallel IHX, and SHX).

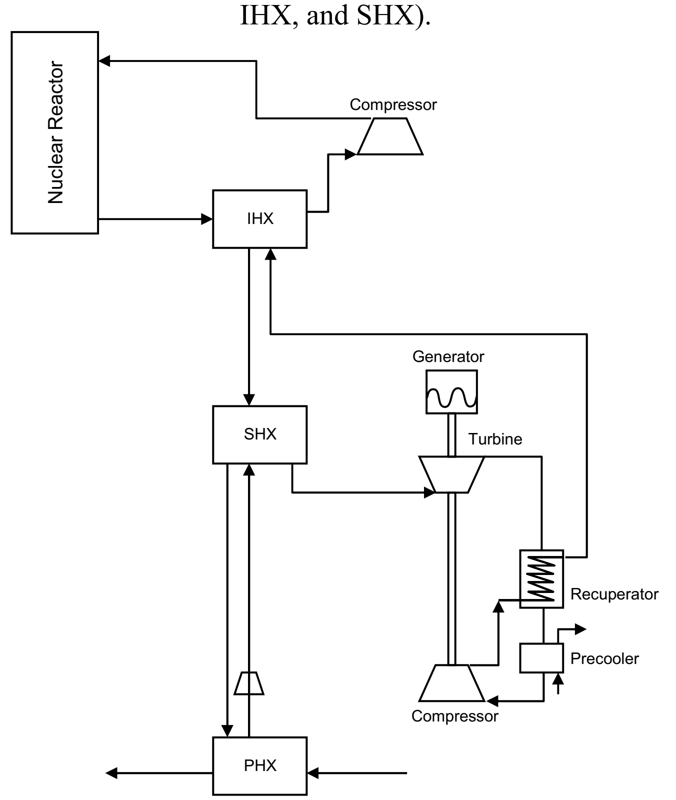

Figure 5. Configuration 5 (indirect electrical cycle and a serial SHX).

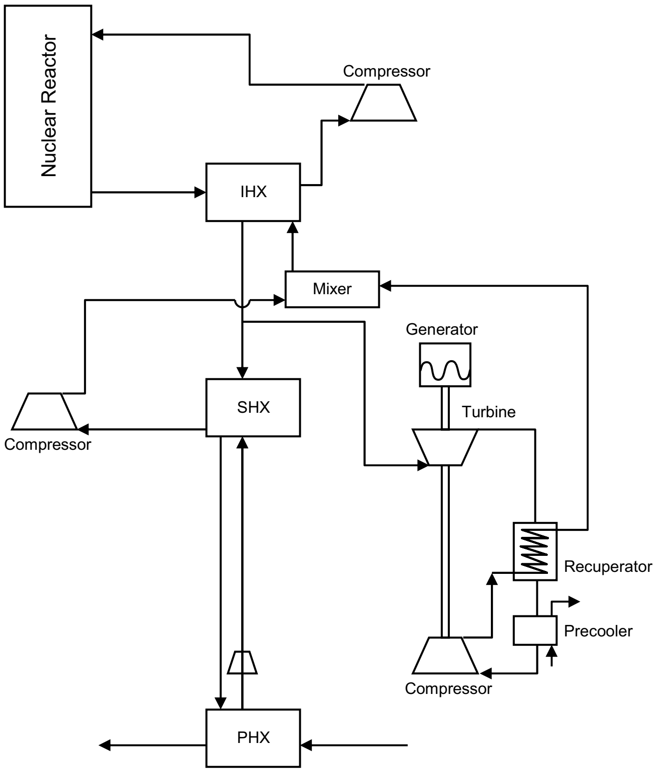

Figure 6. Configuration 6 (indirect electrical cycle and a parallel SHX).

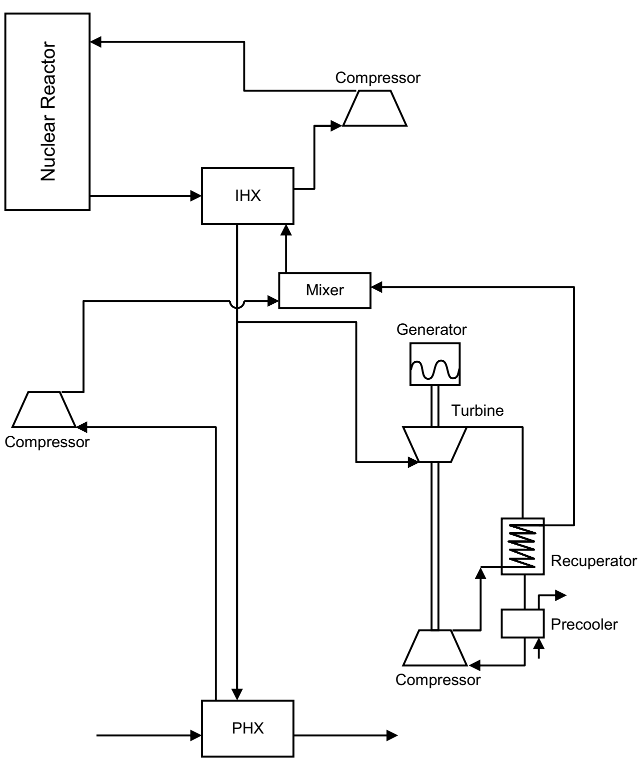

Figure 7. Configuration 7 (indirect electrical cycle and a parallel PHX).

The Independent Technology Review Group (2004) recommended the use of an indirect cycle for the NGNP because it was judged to be more practical for operation and to involve less developmental risk than a direct cycle.

CONCLUSIONS

The overall efficiency of each configuration was evaluated using the HYSYS model. Figure 8 shows a snapshot of the HYSYS simulation of one configuration out of seven configurations. Table 1 summarizes the important parameters in the simulation.

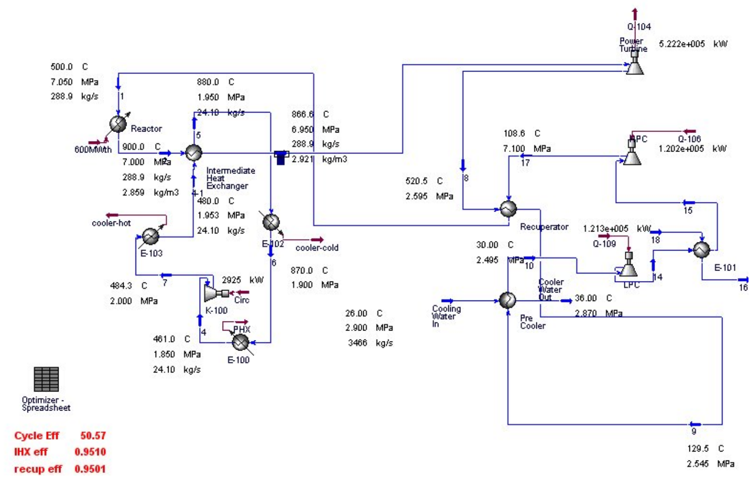

Figure 8. Snapshot of the HYSYS model of Configuration 1.

Table 1 summarizes the results for all seven configurations with helium coolant.

The parametric studies performed in this work indicate the following conclusions.

- The use of an indirect cycle causes the overall efficiency of the plant to decrease by 1.1% compared to a direct cycle based on the temperature drop assumptions used for this analysis.

- The use of a liquid salt as the working fluid in the intermediate heat transport loop of the dual-purpose facility analyzed here causes the overall efficiency to increase by 0.2 – 0.6% compared to low-pressure helium because of reduced pumping power.

- The use of a heat exchanger that is arranged in parallel with the PCU causes the overall efficiency to increase by 0.1 – 0.3% compared to the use a heat exchanger that is arranged in series.

- The variations in overall efficiency were generally small between configurations, except for Configuration 7, where the efficiency was significantly less because of the relatively low operating pressure for this configuration.

- An increase in the reactor outlet temperature of 100 °C caused the overall efficiency to increase by 3.3%.

- An 11% decrease in the flow rate through the turbine caused the overall efficiency to decrease by 1.5%.

Table 1. Efficiency parameters for Configurations 1 through 7.

	Conf-1	**Conf-2**	**Conf-3**	**Conf-4**
PCU configuration	Direct	Direct	Direct	Direct
IHX	Serial	Parallel	Serial	Parallel
SHX	N/A	N/A		
Turbine inlet	866.6 °C	900 °C	866.6 °C	900 °C
	288.9 kg/s	256.8 kg/s	288.9 kg/s	256.8 kg/s
HPC outlet	108.6 °C	119.8 °C	108.6 °C	119.8 °C
	7.1 MPa	7.1 MPa	7.1 MPa	7.1 MPa
Flow rate to IHX (cold side)	24.1 kg/s He	27.5 kg/s He	32.1 kg/s He	27.5 kg/s He
Flow rate to SHX	N/A	N/A	24.38 kg/s He	26.5 kg/s He
Pressure ratio	2.85	3.23	2.83	3.23
Overall cycle efficiency	50.6%	50.7%	50.3%	50.6%
	Conf-5	**Conf-6**	**Conf-7**	
PCU configuration	Indirect	Indirect	Indirect	
IHX				
SHX	Serial	Parallel	N/A	
Turbine inlet	853.7 °C	886.3 °C	880.4 °C	
	292. kg/s	260.1 kg/s	270. kg/s	
HPC outlet	110.3 °C	121.2 °C	144.7 °C	
	7.1 MPa	7.1 MPa	2.0 MPa	
Flow rate to IHX (cold side)	292. kg/s He	292.2 kg/s He	22. kg/s He	
Flow rate to SHX	24.1 kg/s He	27.5 kg/s He	22. kg/s He	
Pressure ratio	2.90	3.29	4.10	
Overall cycle efficiency	49.5%	49.6%	38.6%	

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